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Area Coding Techniques for Monochromatic Visual Displays

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ABSTRACT

A study was conducted to investigate the best coding scheme for differentiating among six different area types on a monochromatic visual display. Three independent variables, coding technique, display background, and foreground line thickness were studied in a 3x2x2 factorial, within-subjects design. Coding technique was studied at 3 levels. Coding technique 1 employed six patterns in one shade of gray, coding technique 2 employed three patterns in each of two shades of gray, and coding technique 3 employed two patterns in each of three shades of gray. Display background was tested at two levels, black and white. Foreground line thickness was also tested at two levels, single pixel thickness and double pixel thickness. Three dependent measures were studied: target memorization time, search time, and percentage selection error. There proved to be no significant difference between coding techniques 1 and 2 at any combination of display background and foreground line thickness for either search time or percentage selection error. Coding technique 3 produced significantly poorer results both for search time and percentage selection error. Target memorization time was lower with coding techniques 1 and 2 and also with double pixel foreground thickness. Subjects preferred coding technique 1 with any combination of display background and line thickness and coding technique 2 with black display background and double pixel foreground line thickness.

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CHAPTER I

INTRODUCTION

The correct use of patterns and colors as codes has significant importance in the design of maps and other graphic information displays. Patterns and colors may be used in such displays to encode point, line, or area information. Refineries, schools, and coal mines are examples of point information, while roadways, rivers, and rail routes are examples of line information. Area information is frequently concerned with qualitative information, such as soil type, type of vegetation, or flood susceptibility. Codes used for area information should not confuse the viewer; they should be distinct enough to permit differentiation even among overlapping codes.

Color codes may be the most common form of code used for qualitative area information on maps. Separate areas depicting acreage devoted to different types of crops can be differentiated easily by the use of different colors. When two or more coded areas overlap, the area of overlap can be coded by an additional color or by the combined use of patterns and colors.

Other coding techniques are necessary when color is not available. This situation arises when monochromatic displays (whether electronic or paper) are employed. In this case, different patterns, cross hatchings, or visual textures may be used to code the areas. The handling of overlapping codes is more difficult when only one color is available.

Overlapping areas may be coded by a superposition of the underlying patterns or by the use of additional patterns, but as the number of patterns increases the user may become overwhelmed.

The problem of differentiating areas by the use of color and/or texture codes is termed the "area fill" problem. When color is unavailable, texture is the primary tool available to set up area displays that will permit accurate and efficient retrieval of qualitative information. This monochromatic area fill problem is of particular relevance to the use of displays to support decision makers in tactical environments. Naval tactical display systems are currently monochromatic and a complete conversion to color graphic displays is not expected to occur in the near future. There is a need for an effective area coding scheme that can be used on the current tactical displays to represent qualitative information concerning combat system configuration and doctrine, system capabilities, and the ship's operating environment. For example, the system should be able to display, on demand, the current and projected physical environment, including weather, communications capabilities, satellite footprints, maps and cartographic backgrounds, reference grids, tactical zones and lanes, fixed and special points and general annotation (Johns Hopkins University, 1984).

CHAPTER II

LITERATURE REVIEW

There have been quite a few investigations of color as a means for coding information. Christ (1975), DeSanctis (1984) and Ives (1982) provide reviews of this work. The work most relevant to the area fill problem is a study of the use of color and visual texture as codes for thematic maps by Phillips and Noyes (1980). Phillips and Noyes compared visual search performance using codes based on either color, texture, or a combination of the two.

A search task was employed because map reading tasks generally have a large search component. Prior research, using as many as eight color codes, indicated that visual search was faster for targets coded by color than for those coded by shape. Thematic maps, however, generally require more than eight area codes. Phillips and Noyes employed displays with 16 codes. They hypothesized that with 16 colors, search times would continue to be fast, but the likelihood of confusions between colors would increase. A combination of both color and texture might then be the best design solution.

Their first experiment employed two types of tasks:

1. search,
2. memorize and search.

In the search task, the target appeared on the same page as the display, while in the memorize and search task the target appeared on the previous page. This experiment also investigated whether the addition of black holding lines between colored areas had any effect on performance.

Displays were printed by offset lithography on 296 mm by 210 mm pages. Each page contained an eight by eight grid of 20 mm by 20 mm squares. There were six types of display:

1. one color/sixteen texture,
2. two color/eight texture,
3. four color/four texture,
4. eight color/two texture,
5. sixteen color/one texture,
6. sixteen color/one texture with black holding lines. The one color display is illustrated in Figure 1. Each square was coded by color, texture, or a combination of the two. There were 4 occurrences of each of 16 different codes, randomly distributed across each display, with the restriction that the same code never appeared in adjacent areas. The colors and textures were chosen by three judges, one of whom was a graphic designer. Test booklets each contained eight different display pages. Each display was the opposite way up from the displays that preceded and followed it to make it difficult for the subjects to learn the displays. Four test booklets were given to the subjects. Booklets 1 and 3 tested the search task only, while booklets 2 and 4 tested the search and memorize task. With booklets 1 and 3, subjects were asked to cross out the four squares that matched the given target. With booklets 2 and 4, subjects were asked to look at the target and then cross out any two examples of it in the display on the following

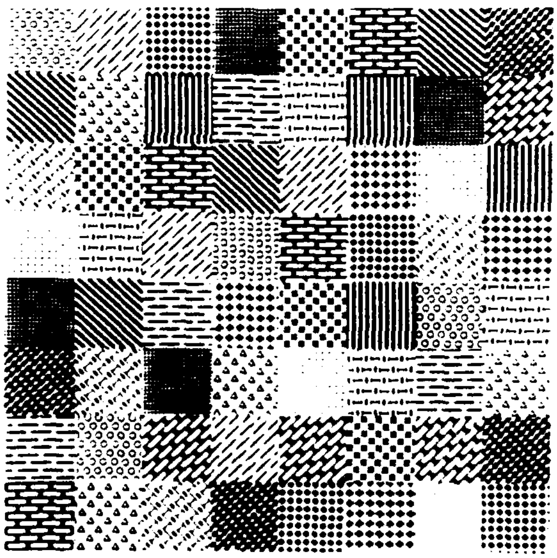


Figure 1. One Color Display.
Reprinted from Phillips and Noyes (1980).

page. Thirty seconds were allowed for the completion of each booklet. The booklets were administered in numbered order with a short break between consecutive booklets.

An analysis of variance for the number of correct responses in each booklet showed statistically significant differences between the six display conditions ($p<0.001$). Duncan's multiple range test showed that the one color condition was worse than all of the other conditions for every booklet ($p<0.05$). There was a general rise in scores as more colors were introduced except for a small, statistically nonsignificant, drop in performance with the four color displays. There was a particularly large increase in score going from one color to two color displays and there was no significant difference between the 16 color displays with and without lines. On the eight and sixteen color displays, most of the errors that occurred were due to confusions of colors which were close together in the color space. The results did not support the prediction that 16 color displays were worse than 8 color displays because of color discriminability problems.

Phillips and Noyes conducted an additional experiment to test the generality of the results of the first experiment. The square grids tested in their first experiment were quite different than the area symbols on a map. Maps generally contain irregularly shaped areas and are usually cluttered by other information along with area symbols. To test whether the addition of visual symbols (such as point and line information) would cause a change in the results of experiment 1, the displays in this experiment were overprinted with irregular map-like curves as well as 'V' and 'O' shaped point symbols. The overprinted display is shown in Figure 2. Booklet 1 was used to perform a search task like that performed in experiment 1. To test the effect of colored and textured area codes on the legibility of point symbols, the subjects were also asked to circle as many of the 'V' shaped symbols (and in a separate condition, the 'O' shaped symbols) as they could in 20 s. This experiment also added a condition that required subjects to remember an area code and then find an example of it after doing some simple arithmetic: Booklet 2 had a 3 page sequence repeated 9 times. The sequence was as follows:

1. a page with the target,
2. a page with 12 simple subtraction tasks,
3. an over printed display page.

The arithmetic page created a 'memory' task similar to that which occurs when one looks at a coded area of a map, turns to another task, and then returns to the map to find another instance of the same code. Time was also limited for this experiment.

The results of the search task showed that the one color condition was significantly worse than all of the other conditions and the two color condition was significantly poorer than the 16 color condition. The results of the search for the 'V' and 'O' symbols showed that it is more difficult to locate point symbols superimposed on areas coded primarily by texture than it is to locate point symbols superimposed on areas coded primarily with color.

An analysis of variance on the memory task for the mean number of errors was not significant. The mean number of errors out of a maximum of eight was 0.41, 0.47, 1.00, and 0.79 for the one, two, eight, and

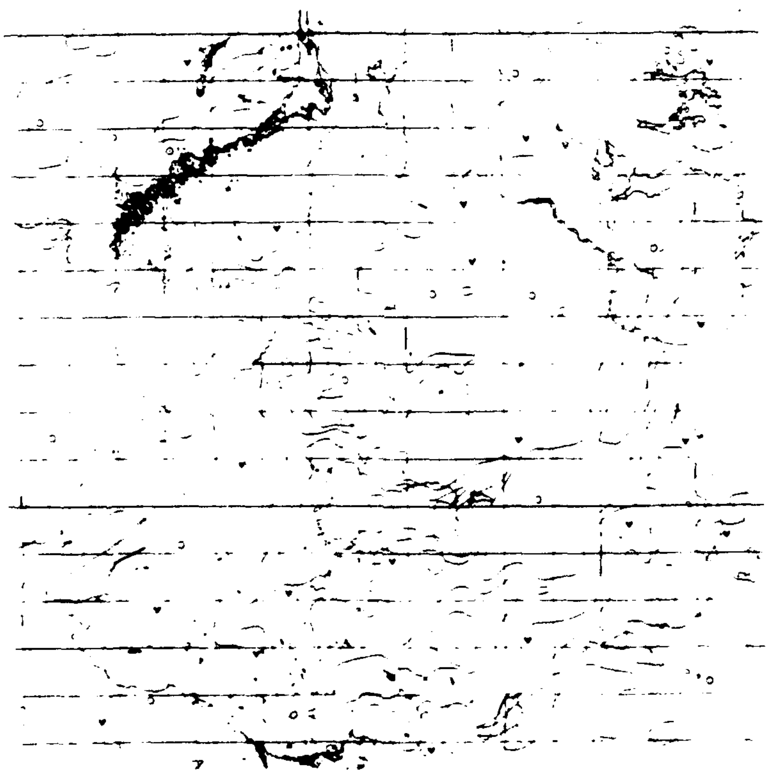


Figure 2. Overprinted display.
Reprinted from Phillips and Noyes (1980).

sixteen color conditions respectively. However, a comparison of the combined scores for the one and two color displays with the combined scores for the eight and sixteen color displays was significant ($p<0.05$). The mean number of errors was greater for the eight and sixteen color displays. The mean numbers of errors for the subtraction task were 1.8, 1.4, 1.4, and 1.9 for the one, two, eight, and sixteen color displays. An analysis of variance was not significant ($p>0.25$).

The results of both the experiments conducted by Phillips and Noyes showed that 'search' was faster with increases in the use of color coding and decreases in the use of texture coding. The experiments also indicated that area symbols coded using two colors in combination with a number of textures are much easier to search among than symbols coded by texture alone; however, superimposed point symbols remain difficult to locate in either of these cases, relative to the cases where area coding is based largely or wholly on color.

Butcher, Eckel, and Patterson (1986) compared the visual coding effectiveness of reverse video and increased pixel density. In one coding method, the luminance was increased around an information source to form a "reverse video" presentation with an average luminance of 12.1 footlamberts, while in the other method, the number of activated pixels within a displayed character was doubled by activating every character pixel (average luminance: 8.1 footlamberts), rather than alternating pixels (average luminance: 3.7 footlamberts). The display consisted of a random combination of either four words or four symbols, placed in the centers of the four quadrants of a computer screen. After the initial display was presented on the screen, one of the words or symbols was highlighted randomly at a time, by increasing either the number of activated pixels or forming a reverse video. This was done after a time delay that was varied randomly between zero and fifteen seconds. Subjects were asked to locate the quadrant containing the cued information by pressing a button, verbally indicating the quadrant location of the stimulus, and identifying the word/symbol. Both response time and accuracy of identification of the quadrant, as well as the word/symbol, were recorded.

The response time for reverse video was significantly lower than that for increased pixel density ($p=0.0195$). The number of incorrect identifications made with reverse video, on the other hand, was greater than the number made with increased pixel density ($p=0.0812$).

Butcher et al. recommend the use of reverse video over increased pixel density to minimize response time. They point out, however, that increased pixel density may be a better choice where high accuracy is required and response time is less important.

Christ and Corso (1983) conducted a series of experiments investigating the effects of extended practice on the evaluation of visual display codes. Letters, digits, familiar geometric shapes, and colored dots were used as codes in visual displays. The experiments employed single code displays (letters, digits, shapes, and dots, used separately) and dual code displays (letters and digits or digits and colored dots used in conjunction) in three isolated tasks (choice reaction, search and locate, and identification-memory) and in a multiple task that combined the three tasks in an irregularly alternating sequence. Of the eight isolated task experiments, five were concerned with performance in a choice reaction task, two with a search and locate task, and one with an identification-memory task.

On the basis of the experiments, Christ and Corso could not conclude that any particular code has any general advantage or disadvantage over any other. The relative effectiveness of the different visual display codes depended upon other display conditions, the task, and the dependent measure used to make the comparison. Thus, a thorough analysis of task requirements must be performed before selecting visual display codes for a task. It also appeared that extensive practice minimized any performance differences that might initially be due to visual display code. Thus, if long-term performance enhancement is an objective, manipulation of code symbology in visual displays may do little to achieve this goal. It should be added, however, that the displays studied in this series of experiments were relatively simple in nature. The contribution of code symbology manipulation to the effectiveness of complex tactical display systems is likely to be much more significant, due to the complexity of clearly coding the large variety of information that must be presented.

Johnston (1968) conducted a study to determine the effects of horizontal resolution and shades of gray on target recognition in an airborne system with particular relevance to targets on the terrain. A third variable, slant range, was also studied, but is not relevant to the area fill problem. In the first part of the study, Johnston determined target recognition time on a TV display when the subjects were permitted to view the targets in advance, while in the second part of the study target recognition time and detection probability were determined without prior viewing of the targets by subjects. A closed circuit TV system was used for the study. Five, seven, and nine shades of gray were used in the study. The shades of gray were varied by using a video clipper which removed video below a preset level.

Only the results of the study that are relevant to the area fill problem are presented here. The first part of the study showed that target recognition time was affected by shades of gray. The target recognition time was lower with nine shades of gray than with five shades of gray. However, there were no significant differences between five and seven shades of gray and between seven and nine shades of gray. In the second part of the study, where subjects were not allowed to view the targets in advance, there were no significant differences between the conditions using different numbers of shades of gray.

CHAPTER III

RESEARCH NEEDS

Although a number of studies have investigated the use of color to present information in graphical form, little appears to have been done to investigate the use of monochromatic patterns as area codes. Phillips and Noyes (1980) compared color coding of areas to textural coding and found color coding to be superior, but they did not focus on the best use of textural coding when color is unavailable. The review of the research literature on the area fill problem suggests that it would be worthwhile to determine the answers to the following questions:

1. Do different sets of patterns have any impact on the processing of information displayed for a given task?
   The patterns tested by Phillips and Noyes were selected in consultation with a graphics designer. A completely different group of patterns might be tested in the same way to see if the results tally with those for the patterns tested by Phillips and Noyes. If the results differ, then close attention must be paid to pattern selection.

2. What area fill patterns work best together and how many of them can be used at a time?

3. What types of patterns can be used together when there is a possibility of overlap among differently coded areas?
   Map designers have dealt with the problem of overlap by combining the use of color codes with texture codes. This approach is not possible with monochromatic displays.

4. Can performance with a given set of monochromatic area fill codes be enhanced by delineating the borders of each coded area with solid "holding" lines?
   Phillips and Noyes (1980) investigated the effect of printing black holding lines 0.2 mm wide around and between colored areas. No difference in performance was found between the color displays with lines and without lines. The effect of printing holding lines around and between the textured areas was not investigated, however. Phillips and Noyes' studies indicate that it is more difficult to perform search tasks with

texture codes. Therefore any performance enhancements holding lines provide may be more apparent and of greater practical utility when used to help delineate textured areas, rather than colored areas. The effect of the contrast of the holding line against the display background might also be tested by studying a particular display with black holding lines as well as with white holding lines delineating the borders of the coded areas. The effect of holding line thickness might also be tested. Phillips and Noyes (1980) conducted their study using only one holding line thickness.

5. Given the findings of Phillips and Noyes (1980) that, for 16 area codes, the use of color and texture coding together is more effective than the use of texture alone, is it possible that the use of shades of gray and texture together might be more effective than the use of texture alone? This approach can be implemented on monochromatic displays, while the combination of color with textural codes, of course, cannot. Johnston's (1968) study found that target recognition performance improved with increasing number of shades of gray when subjects were allowed to view the target in advance. The area fill problem is quite different from the target recognition problem studied by Johnston, but the use of shades of gray may enhance performance in a similar fashion.

6. For a given set of monochromatic patterns, can performance be enhanced if the patterns are displayed on a dark background or is it better to display patterns on a light background? Pawlak (1986) compared video display units with light display background to units with dark display background and cited two earlier studies that reported improved performance as well as greater subjective preference with light display background. However, Zwahlen and Kothari (1986) studied operator performance, behavior, and subjective comfort using video display units and found no significant differences between light and dark display backgrounds if sufficient luminance contrast was provided between the background and the foreground characters. It remains to be seen how performance with patterns displayed in shades of gray is affected by the background shade of the video display unit.

7. Is performance with coding techniques using more than one shade of gray enhanced by increasing the thickness of the lines used to create the patterns?
It would seem that a thicker line, by providing a more discernible shaded area, would ease discrimination among areas coded with different shades of gray.

The following sections of this report present the design, analysis, and results of an experimental study that focuses upon the last three research questions listed above.

CHAPTER IV

EXPERIMENTAL DESIGN

The purpose of this research was to investigate whether the combined use of shades of gray and texture was more effective than the use of texture alone for coding areas on a monochromatic video display. Three independent variables were investigated in a 3x2x2 factorial within-subjects design. Figure 3 provides a graphic representation of the design.

Independent Variables

The three independent variables studied were coding technique (C), display background (B), and foreground line thickness (T).

Coding technique. This variable was studied at 3 levels. Each level employed a code set consisting of six codes. The three levels of this variable were:

1. Six patterns in one shade of gray;
2. Three patterns in each of two shades of gray;
3. Two patterns in each of three shades of gray;

The patterns employed are defined in Appendix A for each level of foreground line thickness. The coding technique variable permitted testing whether texture alone or a combination of texture and shades of gray was a more effective coding technique for the production of six different codes.

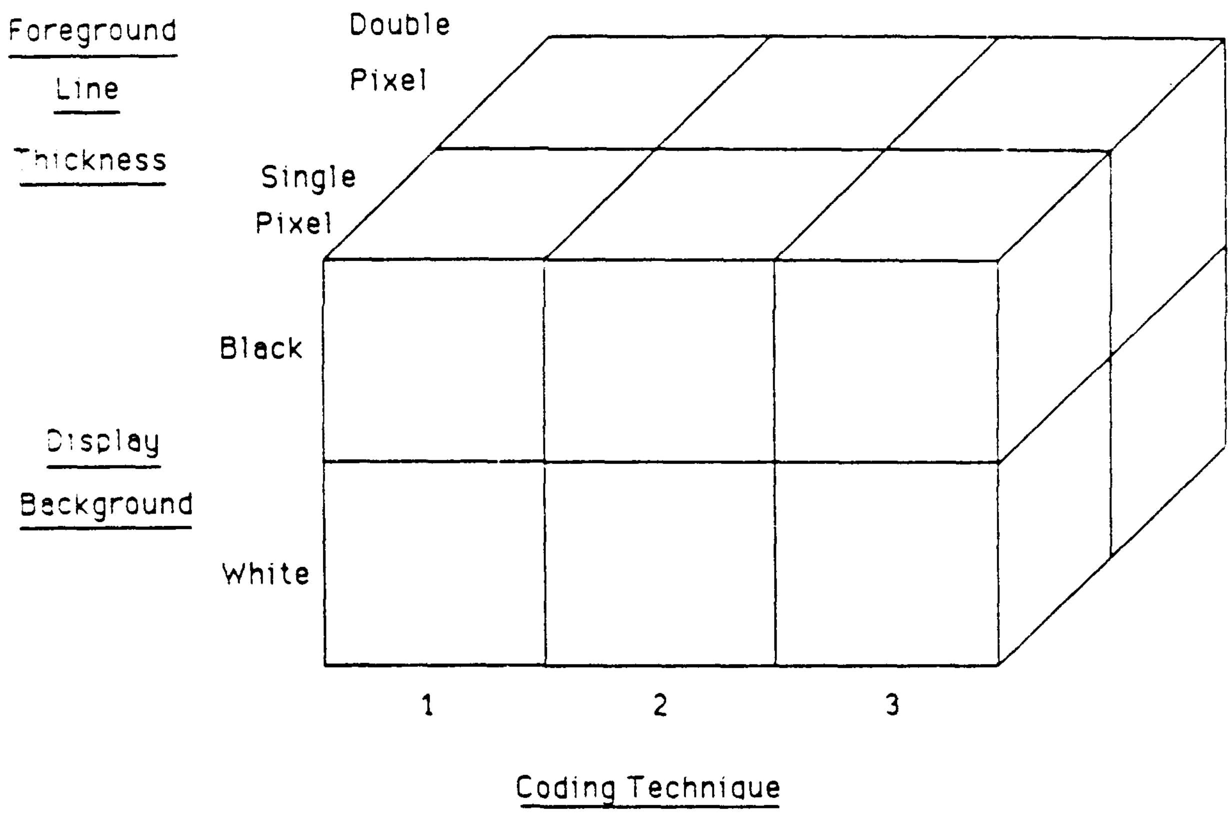


Figure 3. Representation of the Experimental Design.

Display background. This independent variable was studied at two levels:

1. Black background: In this case the foreground was white, light gray, and dark gray for coding technique 3; white and dark gray for coding technique 2; white for coding technique 1.

2. White background: In this case the foreground was black, dark gray, and light gray for coding technique 3; black and light gray for coding technique 2; black for coding technique 1.

Inclusion of this variable allowed testing whether display background affected performance when presenting area codes using a combination of pattern and shades of gray on a monochromatic display.

Line thickness. This independent variable was also studied at two levels. Patterns were composed of lines with either single pixel thickness or double pixel thickness. The patterns are defined in Appendix A for each level of line thickness. With single pixel thickness lines, patterns 1 through 6 were used with coding technique 1; patterns 1, 2, and 3 were used with coding technique 2; and patterns 1 and 2 were used with coding technique 3. With double pixel thickness lines, patterns 7 through 12 were used with coding technique 1; patterns 7, 8, and 9 were used with coding technique 2; and patterns 7 and 8 were used with coding technique 3. This variable permitted testing whether patterns composed of double pixel thickness lines improved performance compared to patterns with single pixel thickness lines.

Task

A "memorize and search" task was employed. At the beginning of each block of trials, the subject was shown the set of codes that was employed on the trials in that block (see Figure 4). Pressing the

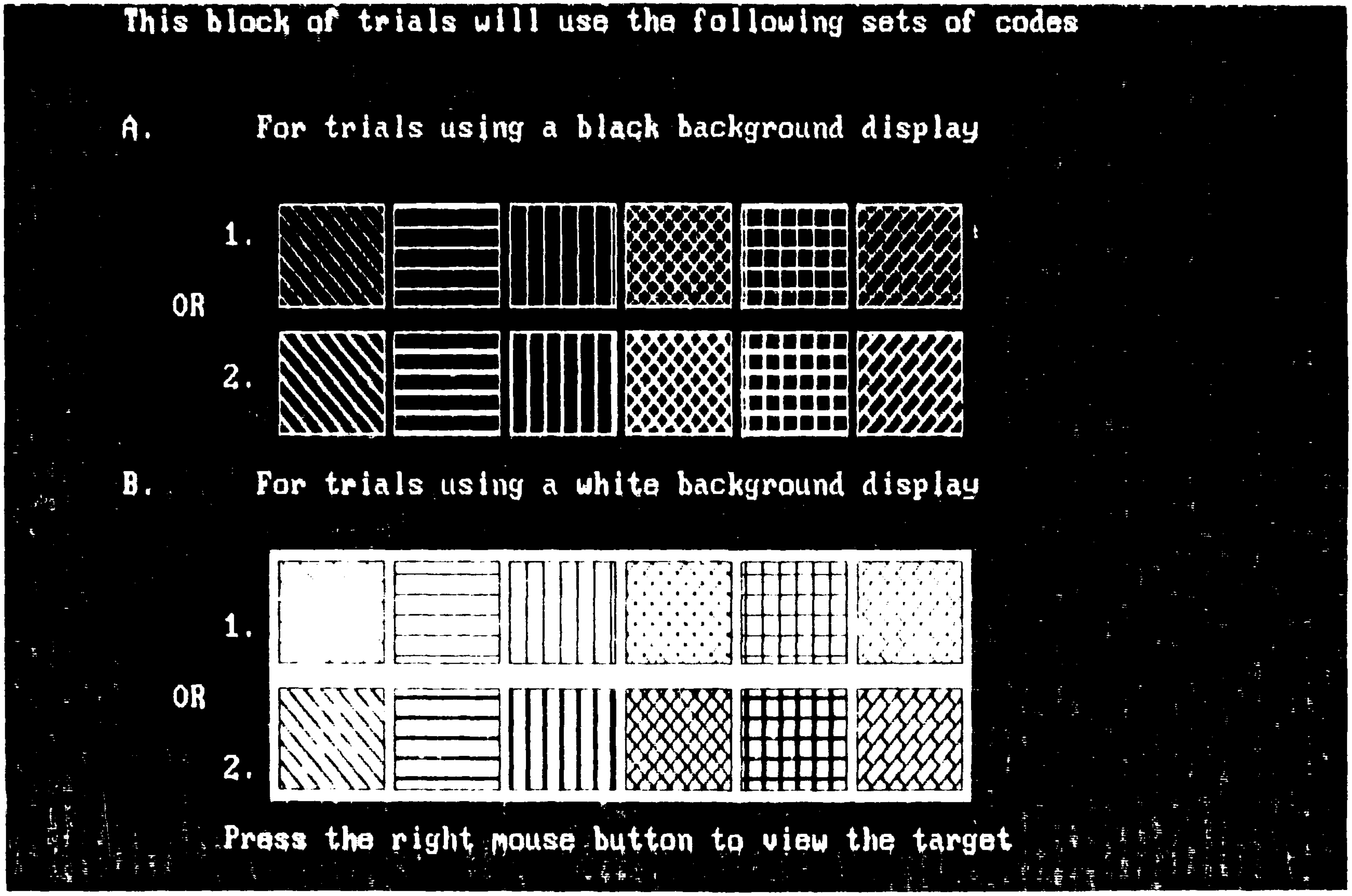


Figure 4. Example code set for a block of trials.

right mouse button cleared the screen and initiated display of a one inch by one inch target on the screen (see Figure 5). Subjects were asked to study the target and press the right mouse button when they were ready to search for this target on the test display. Pressing the mouse button cleared the screen and generated a test display (see Figure 6). A tone was generated at the same time to signal the start of the timer. The test display contained a three inch by four inch grid, which contained twelve one inch by one inch coded areas. The target code always appeared two times within the grid. The subject's task was to locate each of the two occurrences of the previously displayed target on the grid. The subject was then to move a displayed cursor to each of those targets and to press the right mouse button when the cursor was within a target to confirm his choice. A tone was generated whenever a selection was made. After the subject finished entering the two selections, he was given feedback regarding the accuracy of his selections. He was then told to clear the display by pressing the right mouse button, whereupon a new target display was generated. There was no time limit on the task, but the subjects were asked to make their selections as quickly and as accurately as possible.

Procedure

Potential subjects were tested for corrected 20/20 vision at a distance of 20 inches. On successful completion of the eye test, subjects were asked to read the participant's informed consent (Appendix B). Subjects willing to participate in the study were instructed on the use of the mouse to locate and enter their selections (Appendix C).

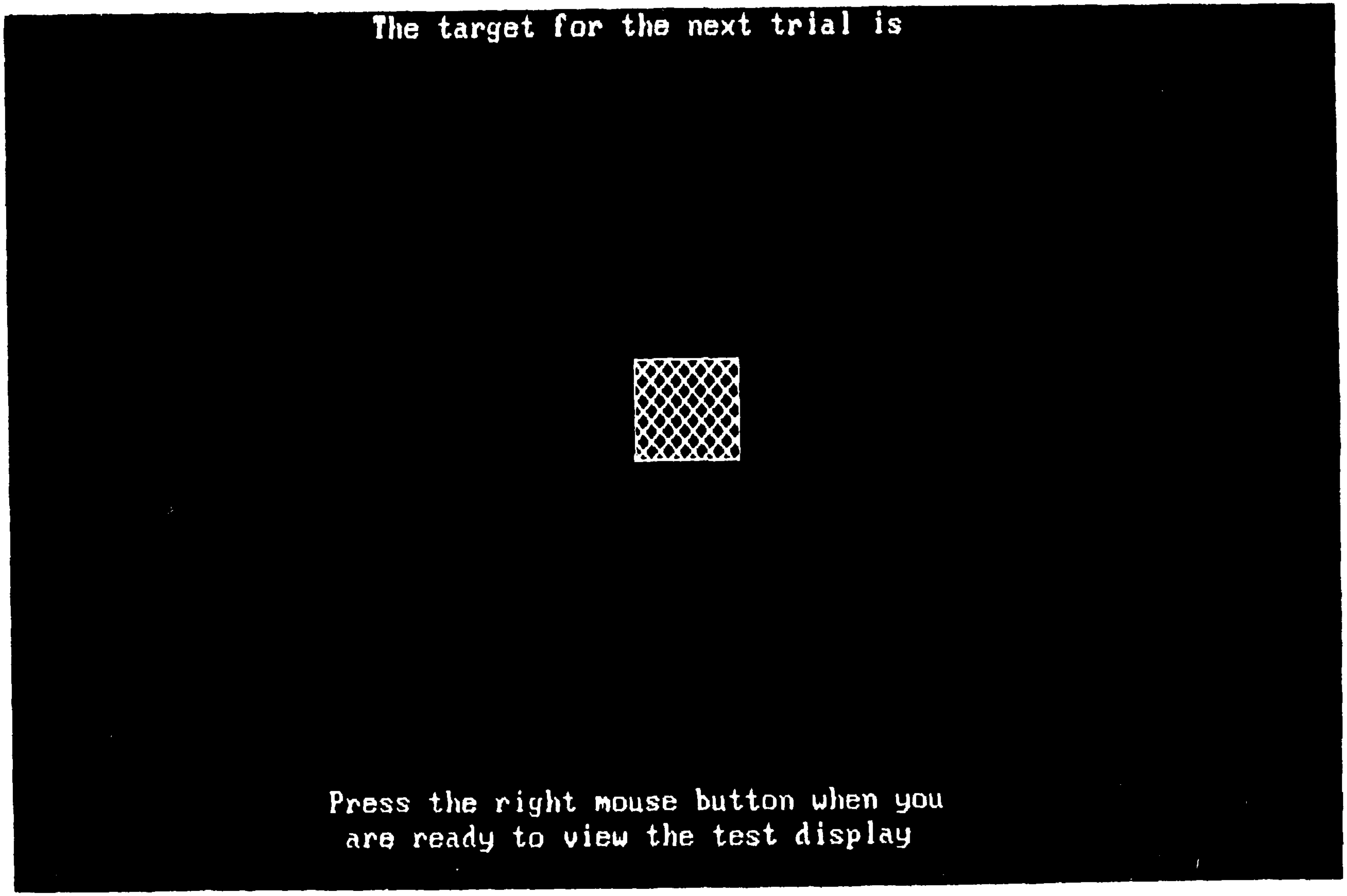


Figure 5. Example of the target display.

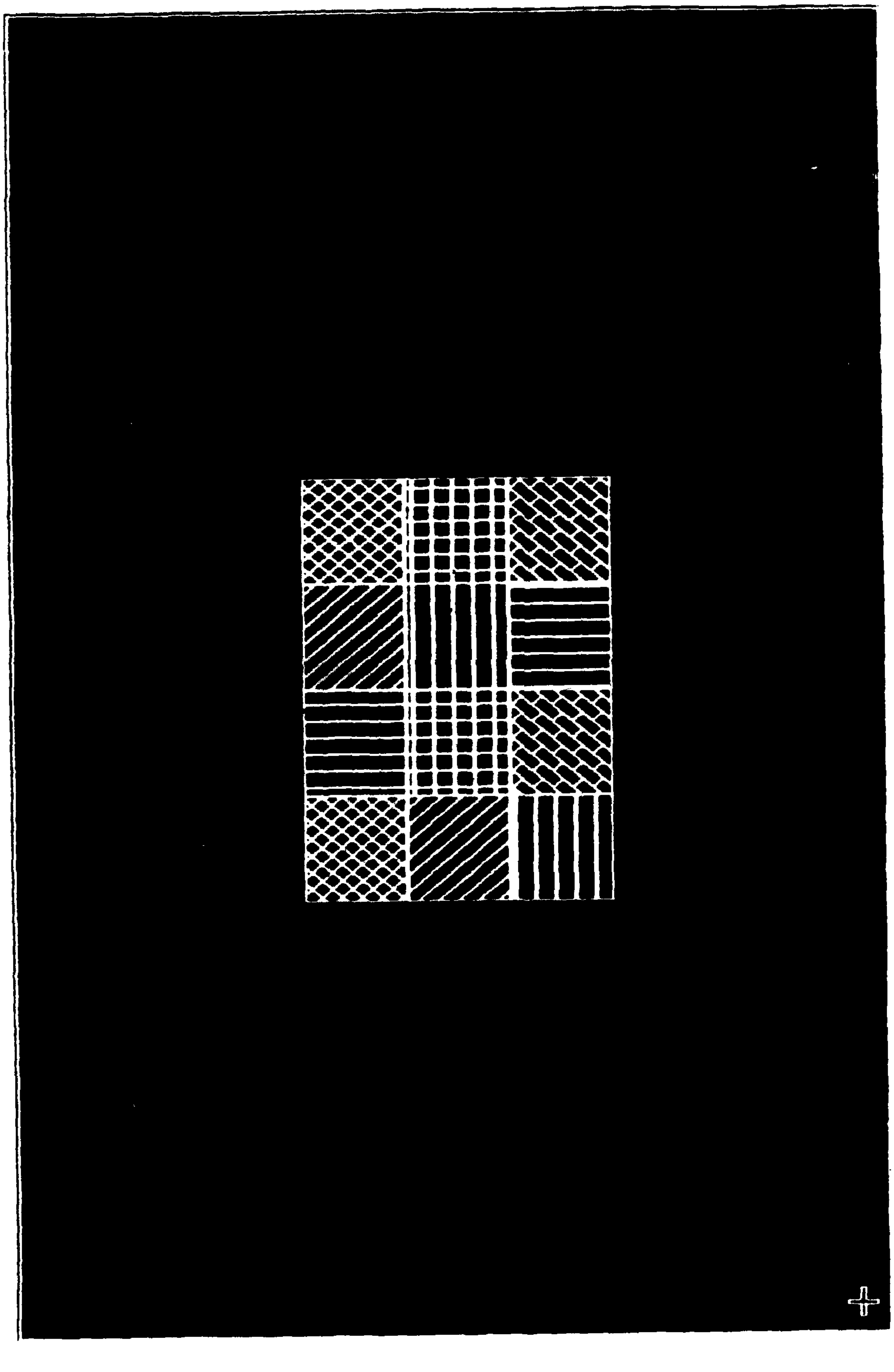


Figure 6. Example of the test display.

Subjects were informed that they would see three different code sets which employed patterns and shades of gray as coding dimensions. They were told that each block of trials would use only one code set, but that it would be employed in combination with each of two display backgrounds and two line thicknesses as shown in Figure 7.

Each subject performed a set of 20 training trials comprising five instances of each of the four display background/line thickness combinations for a particular coding technique. A test block of 40 trials was then administered comprising ten instances of the four display background/line thickness combinations for the same coding technique. Three blocks of training and test trials were administered to each subject. The order of testing of the three blocks was completely counterbalanced across subjects, and the order of testing of the four conditions within a block of trials was randomized, subject to the constraint that ten occurrences of each of the conditions occurred in each block of trials. Rest breaks between blocks were provided to minimize any learning effects across the test blocks. The same 10 pairs of target code locations within the three row by four column grid were used for each of the four treatment conditions within each of the three blocks of test trials. The locations of coded areas within the grid were subject to the constraint that no occurrences of the same code were allowed to share a common line boundary. A tone was generated and a timer started the moment the test display appeared on the screen. The cursor appeared at a fixed location on the lower left corner of the test display in all trials. The three inch by four inch grid containing the twelve codes was centered on the display. Each time the right

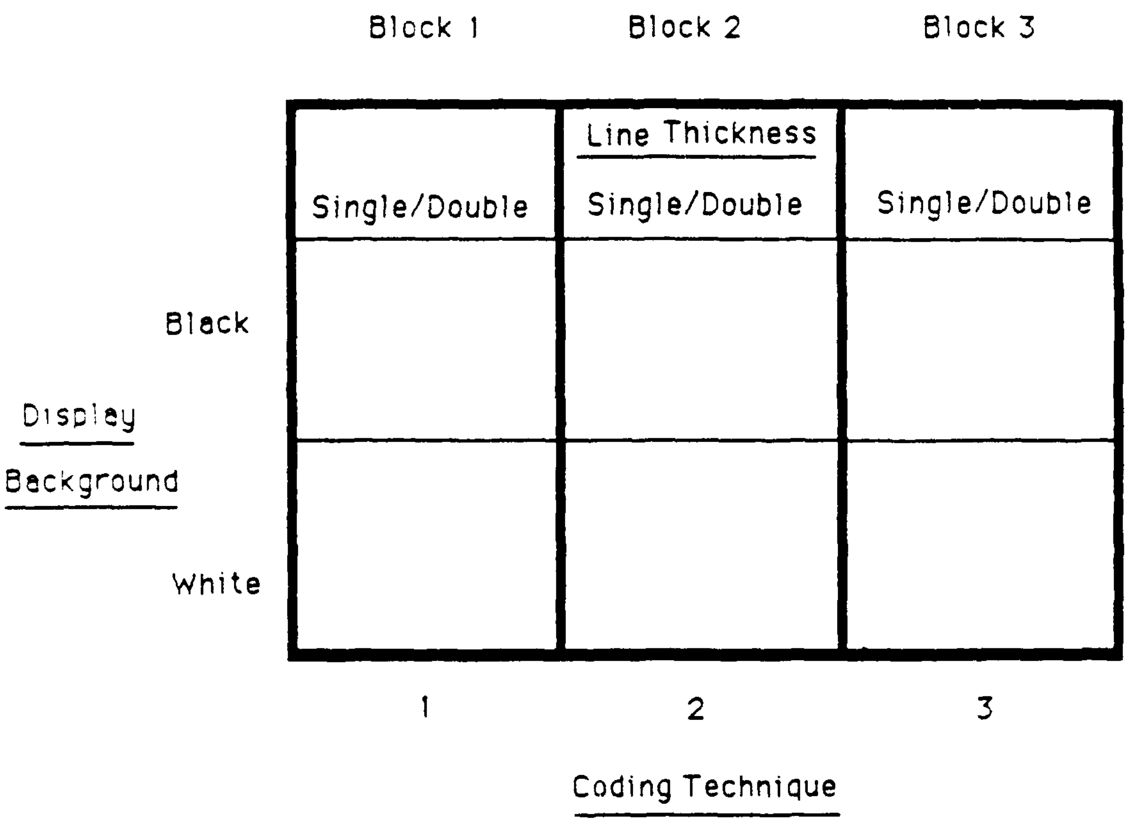


Figure 7. Representation of the blocks.

mouse button was pressed to select a target, a tone was generated. Upon entry of the second target selection, the subject was given feedback regarding the accuracy of his selections. When the subject was ready to begin the next trial, a press of the right mouse button cleared the display and initiated generation of the next target display.

Apparatus

The hardware configuration consisted of a Tandy 3000HD personal computer with keyboard and mouse interfaced to a NEC Multisync (JC-1401P3A) monitor. The resolution of the display was 640 pixels x 350 pixels measured across an active display area of 250 mm (horizontal) by 180 mm (vertical). The display/control gain of the mouse was adjusted to yield 1.4 cm of display cursor movement per centimeter of mouse movement.

Subjects

Eighteen male college students participated in the study. All participants were screened for corrected 20/20 vision (that is, with glasses or contacts) for an intermediate distance of 20 inches. This closely approximated the distance from the normal position of the subject's eyes to the CRT display.

Dependent variables

The primary performance measures collected during the study were 'target memorization time', 'search time' and 'percentage selection error'. Target memorization time was defined as the time from the presentation of the target display until the subject pressed the mouse to view the test display. Search time was defined as the time from the presentation of the test display until the entry of the second target selection. Percentage selection error was measured as the number of incorrect selections made out of the total number of opportunities.

Upon completion of the last treatment block, subjects were asked to rank the twelve different combinations of coding technique, display background, and line thickness in order of preference from most preferred to least preferred (Appendix D).

CHAPTER V

RESULTS

Data Collection

At the beginning of each block of trials the clock was initialized. The first clock reading occurred when the example target appeared on the display. The clock was again read at the following events:

1. Completion of viewing of the example target,
2. Appearance of the test display,
3. First movement of the mouse,
4. First entry of the cursor into the grid of patterns,
5. Selection of the first target,
6. Selection of the second target.

The correctness of each of the two target selections was also recorded during each trial.

Data Reduction

The raw data was manipulated to obtain the target memorization times, the search times, and the percentage selection error. Statistical analyses were then carried out on each of these reduced data sets.

Analysis

Analyses of variance (ANOVA) were carried out for each of the three dependent measures: target memorization time, search time, and percentage selection error. Significant effects were further investigated using post-hoc Newman-Keuls comparisons. An alpha level of 0.05 was used as the criterion for significance in all the tests.

Target memorization time. The results of an analysis of variance of target memorization times are presented in Table 1. There were significant main effects of coding technique and foreground line thickness. Newman-Keuls comparisons (Table 2) show that target memorization time was significantly higher for coding technique 3 than the other two coding techniques, but that there was no significant difference in memorization times for coding techniques 1 and 2. Subjects took more time to memorize codes with a single pixel line thickness (1.94 s) than codes with a double pixel line thickness (1.81 s).

Search time and percentage selection error. The results of the analyses of variance for search time and percentage selection error are presented in Tables 3 and 4, respectively. The three-way interaction among coding technique, display background, and foreground line thickness was significant for both search time and percentage selection error. These interactions are shown in Figures 8 and 9. The three-way interactions were further investigated with a series of simple-effects F tests at each of the three levels of coding technique (Tables 5 and 6). The simple two-way interaction of display background and line thickness was significant at coding technique 3 for both search time and percentage selection error (Tables 5 and 6). Newman-Keuls comparisons for these simple two-way interactions are summarized in Table 7. The results show that at coding technique 3 search time is significantly longer when a white display background is used with single pixel line

TABLE 1. Analysis of Variance Summary Table for Target Memorization Time:

Source	df	SS	F	p
Between				
Subjects (S)	17	524.28		
Within				
Coding Technique (C)	2	102.38	12.93	0.0001 *
C x S	34	134.63		
Display Background (B)	1	1.63	3.59	0.0751
B x S	17	7.74		
Line Thickness (T)	1	0.91	5.43	0.0324 *
T x S	17	2.87		
C x B	2	0.38	0.61	0.5497
C x B x S	34	10.78		
C x T	2	0.10	0.25	0.7780
C x T x S	34	6.90		
B x T	1	0.45	2.18	0.1585
B x T x S	17	3.53		
C x B x T	2	0.13	0.30	0.7395
C x B x T x S	34	7.50		
Total	215	804.26		

TABLE 2. Newman-Keuls Comparisons for the Target Memorization Time: Comparing Coding Technique Means

Technique	Means	Comparisons
Technique 1	1.282	A
Technique 2	1.521	A
Technique 3	2.847	B

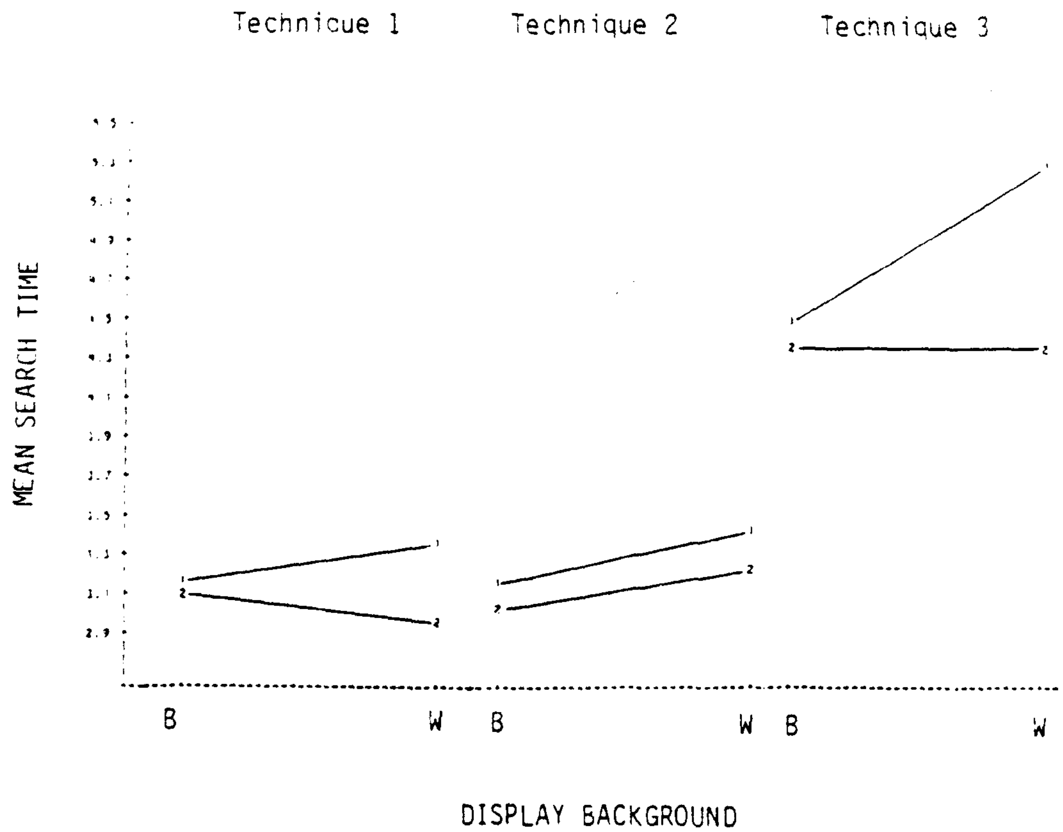
Note: Means with the same letter are not significantly different.

TABLE 3. Analysis of Variance Summary Table for Search Time

Source	df	SS	F	p	
Between					
Subjects (S)	17	129.20			
Within					
Coding Technique (C)	2	103.04	17.64	0.0001	*
C x S	34	99.31			
Display Background (B)	1	2.70	6.60	0.0199	*
B x S	17	6.96			
Line Thickness (T)	1	5.45	10.33	0.0051	*
T x S	17	8.98			
C x B	2	1.22	1.73	0.1919	
C x B x S	34	12.01			
C x T	2	1.49	1.76	0.1871	
C x T x S	34	14.42			
B x T	1	2.18	9.51	0.0067	*
B x T x S	17	3.89			
C x B x T	2	1.27	3.58	0.0388	*
C x B x T x S	34	6.03			
Total	215	398.21			

TABLE 4. Analysis of Variance Summary Table for Percentage Selection Error:

Source	df	SS	F	p
Between				
Subjects (S)	17	88.02		
Within				
Coding Technique (C)	2	441.81	65.59	0.0001 *
C x S	34	114.51		
Display Background (B)	1	16.11	5.09	0.0375 *
B x S	17	53.80		
Line Thickness (T)	1	1.04	0.68	0.4195
T x S	17	25.87		
C x B	2	32.25	6.94	0.0030 *
C x B x S	34	79.07		
C x T	2	2.11	0.83	0.4445
C x T x S	34	43.22		
B x T	1	24.67	9.62	0.0065 *
B x T x S	17	43.57		
C x B x T	2	31.59	7.12	0.0026 *
C x B x T x S	34	75.40		
Total	215	1073.10		



B = Black Display Background
W = White Display Background
1 = Single Pixel Foreground
Line Thickness
2 = Double Pixel Foreground
Line Thickness

Figure 8. Plot of Display background by Line Thickness Interaction at levels of Coding Technique for Search Time.

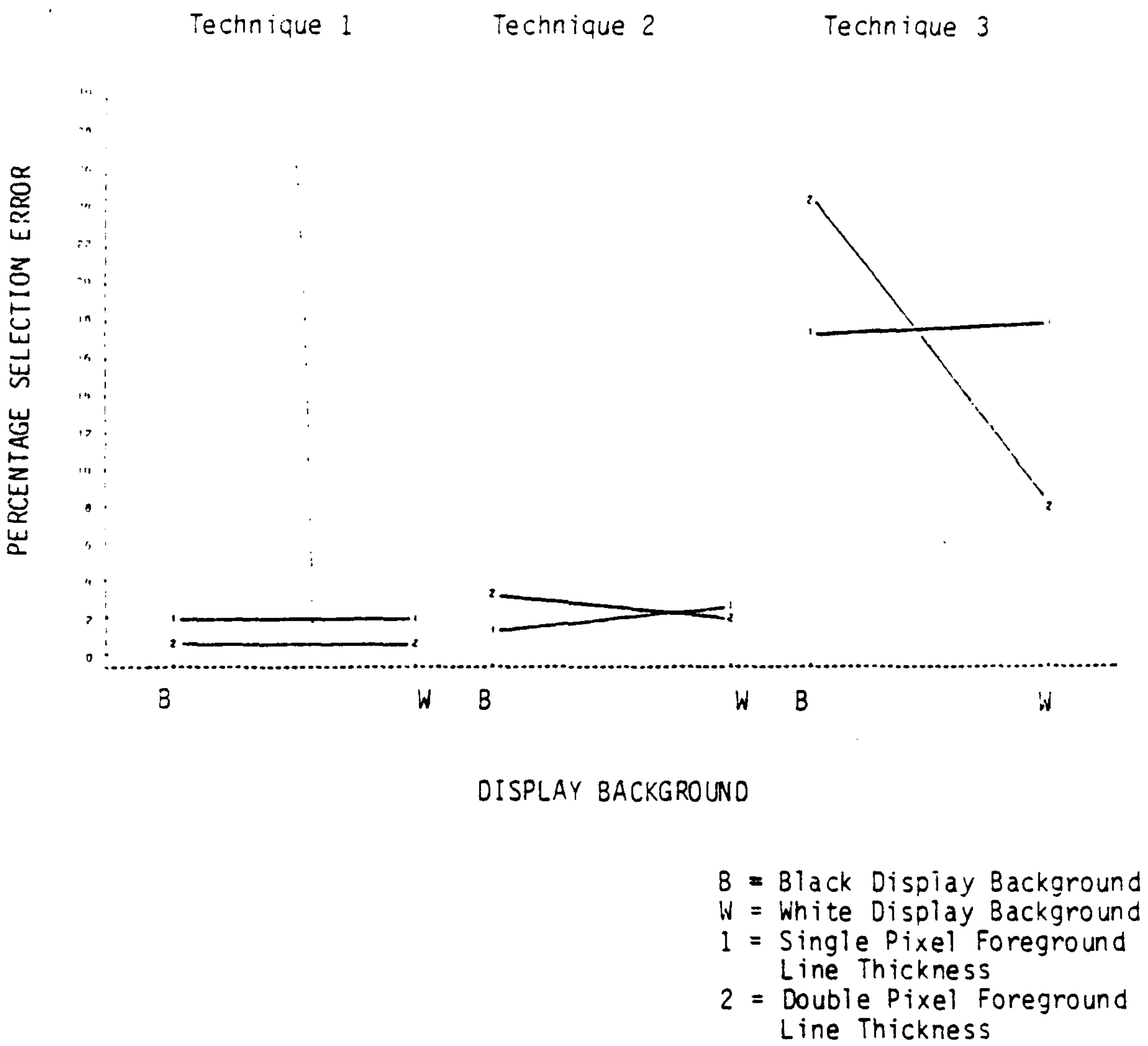


Figure 9. Plot of Display Background by Line Thickness Interaction at levels of Coding Technique for Percentage Selection Error.

TABLE 5. Summary Table of the Simple-Effects F Test for Search Time:

Source	df	SS	F	p
Coding Technique 1				
Display Background (B)	1	0.019	0.07	0.8014
Line Thickness (T)	1	0.938	8.64	0.0092 *
B * T	1	0.342	4.63	0.0561
Coding Technique 2				
Display Background (B)	1	1.197	5.48	0.0317 *
Line Thickness (T)	1	0.547	3.41	0.0824
B * T	1	0.049	0.81	0.3801
Coding Technique 3				
Display Background (B)	1	2.72	3.73	0.0702
Line Thickness (T)	1	5.46	4.94	0.0402 *
B * T	1	3.05	6.81	0.0183 *

TABLE 6. Summary Table of the Simple-Effects F Test for Percentage Selection Error:

Source	df	SS	F	p
<u>Coding Technique 1</u>				
Display Background (B)	1	0.013	0.05	0.8344
Line Thickness (T)	1	1.125	6.12	0.0242 *
B * T	1	0.013	0.03	0.8675
<u>Coding Technique 2</u>				
Display Background (B)	1	0.01	0.01	0.9142
Line Thickness (T)	1	0.34	0.63	0.4391
B * T	1	1.12	1.51	0.2352
<u>Coding Technique 3</u>				
Display Background (B)	1	48.34	7.62	0.0134 *
Line Thickness (T)	1	1.68	0.51	0.4869
B * T	1	55.12	9.55	0.0066 *

TABLE 7. Newman-Keuls comparisons of the Simple Display Background by Foreground Line Thickness Interaction at Coding Technique 3

Display Background	Line Thickness	Means	Comparisons
	Search Time		
White	2	4.36	A
Black	2	4.38	A
Black	1	4.52	A
White	1	5.32	B
	Percentage Selection Error		
White	2	1.55	A
Black	1	3.50	B
White	1	3.61	B
Black	2	4.94	B

Note: Means with the same letter are not significantly different.

thickness codes than it is with the other three display background/foreground line thickness combinations, while percentage selection error is significantly lower when a white display background is used with double pixel line thickness codes than it is with the other three display background/foreground line thickness combinations.

The simple main effect of foreground line thickness was also significant at coding technique 3 for search time (Table 5). Double pixel line thickness resulted in lower search times than single pixel line thickness. The underlying simple two-way interaction of display background with line thickness, however, indicates that this result is not generally true. Double pixel line thickness results in lower search times than single pixel line thickness at coding technique 3 only if the display background is white.

The simple main effect of display background was significant at coding technique 3 for percentage selection error (Table 6). The white display background resulted in lower percentage selection error than the black display background. The underlying simple two-way interaction of display background with line thickness, however, indicates that the white display background results in lower percentage selection error than the black display background at coding technique 3 only if the foreground line thickness is double pixel.

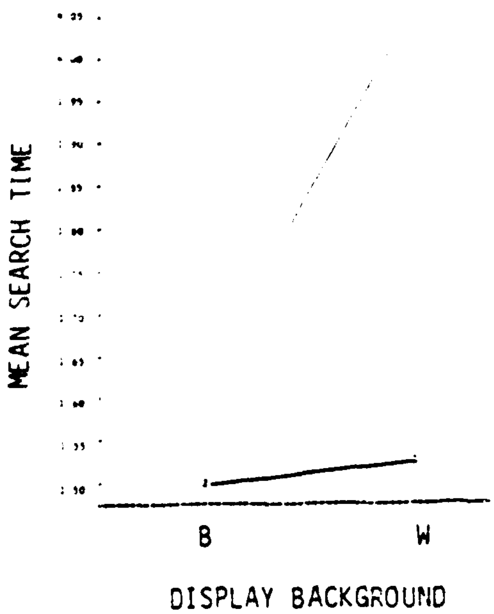
The simple two-way interaction of display background and foreground line thickness neared significance at coding technique 1 for search time (Table 5). This suggests that search times may be lower when double pixel foreground line thickness is used with a white background at coding technique 1 than when single pixel foreground line thickness is used with a white background.

The simple main effect of foreground line thickness was significant at coding technique 1 for both search time and percentage selection error (Tables 5 and 6). The double pixel foreground line thickness generally resulted in shorter search times (3.05 s) and lower percentage selection error (0.7%) than the single pixel line thickness (3.28 s and 1.95%, respectively) at coding technique 1.

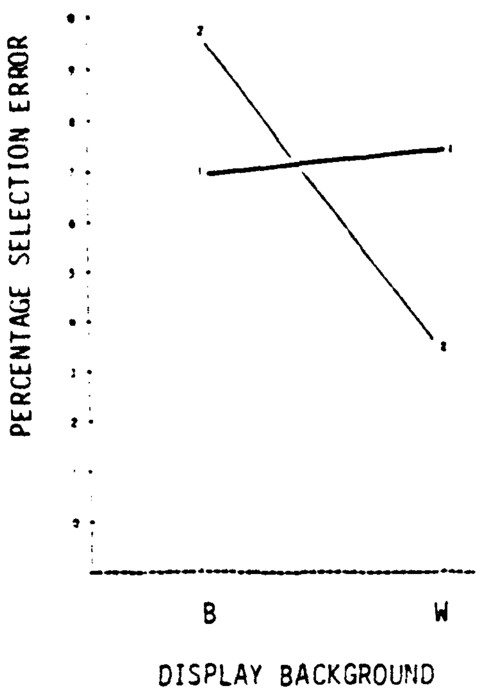
The simple main effect of display background was significant at coding technique 2 for search time (Table 5). Search time was generally lower when the display background was black (3.07 s) than when it was white (3.34 s) at coding technique 2.

The two-way interaction between display background and foreground line thickness was significant for both search time and percentage selection error (Figure 10). Newman-Keuls comparisons are summarized in Table 8. The Newman-Keuls tests for search time indicate that search time for codes using a white display background with single pixel foreground line thickness is significantly longer than search times for codes using the other three combinations of display background and foreground line thickness. The significant three-way CxBxT interaction depicted in Figure 8, however, indicates that these observations are primarily a result of the simple interaction of display background and foreground line thickness for coding technique 3. Similarly, the Newman-Keuls tests for percentage selection error indicate that fewer errors are committed with codes using a white display background and double pixel foreground line thickness than with codes using the other three combinations of display background and foreground line thickness.

Search Time



Percentage Selection Error



B = Black Display Background
W = White Display Background
1 = Single Pixel Foreground Line Thickness
2 = Double Pixel Foreground Line Thickness

Figure 10. Plot of Display Background by Line Thickness Interaction.

TABLE 8. Newman-Keuls comparisons of the Display background by Foreground Line Thickness Interaction

Display Background	Line Thickness	Means	Comparisons	
		Search Time		
Black	2	3.50	A	
White	2	3.52	A	
Black	1	3.62	A	
White	1	4.04		B
		Percentage Selection Error		
White	2	0.76	A	
Black	1	1.37		B
White	1	1.55		B
Black	2	1.93		B

Note: Means with the same letter are not significantly different.

Again, however, the significant three-way CxBxT interaction depicted in Figure 9 indicates that these observations are a result of the simple interaction of display background and foreground line thickness for coding technique 3.

The two-way interaction of coding technique with display background was significant for percentage selection error (Figure 11). The results of a Newman-Keuls test are summarized in Table 9. Error rate is sensitive to display background with coding technique 3, but not with coding techniques 1 and 2. The significant three way CxBxT interaction depicted in Figure 9, however, makes it clear that this effect is confounded with foreground line thickness. Error rate is sensitive to display background only when coding technique 3 is used with double pixel foreground line thickness. In this case, error rates are significantly lower with the white display background than with the black display background.

The main effect of coding technique was significant for search time and percentage selection error. Newman-Keuls tests indicate that search time was significantly longer and percentage selection error was significantly higher for coding technique 3 than for the other two coding techniques (Tables 10 and 11). Search time and percentage selection error performance was not significantly different for coding techniques 1 and 2.

The main effect of display background was significant for search time and percentage selection error. The black display background resulted in shorter search times than the white display background (3.56 s for black display background vs 3.78 s for white display background),

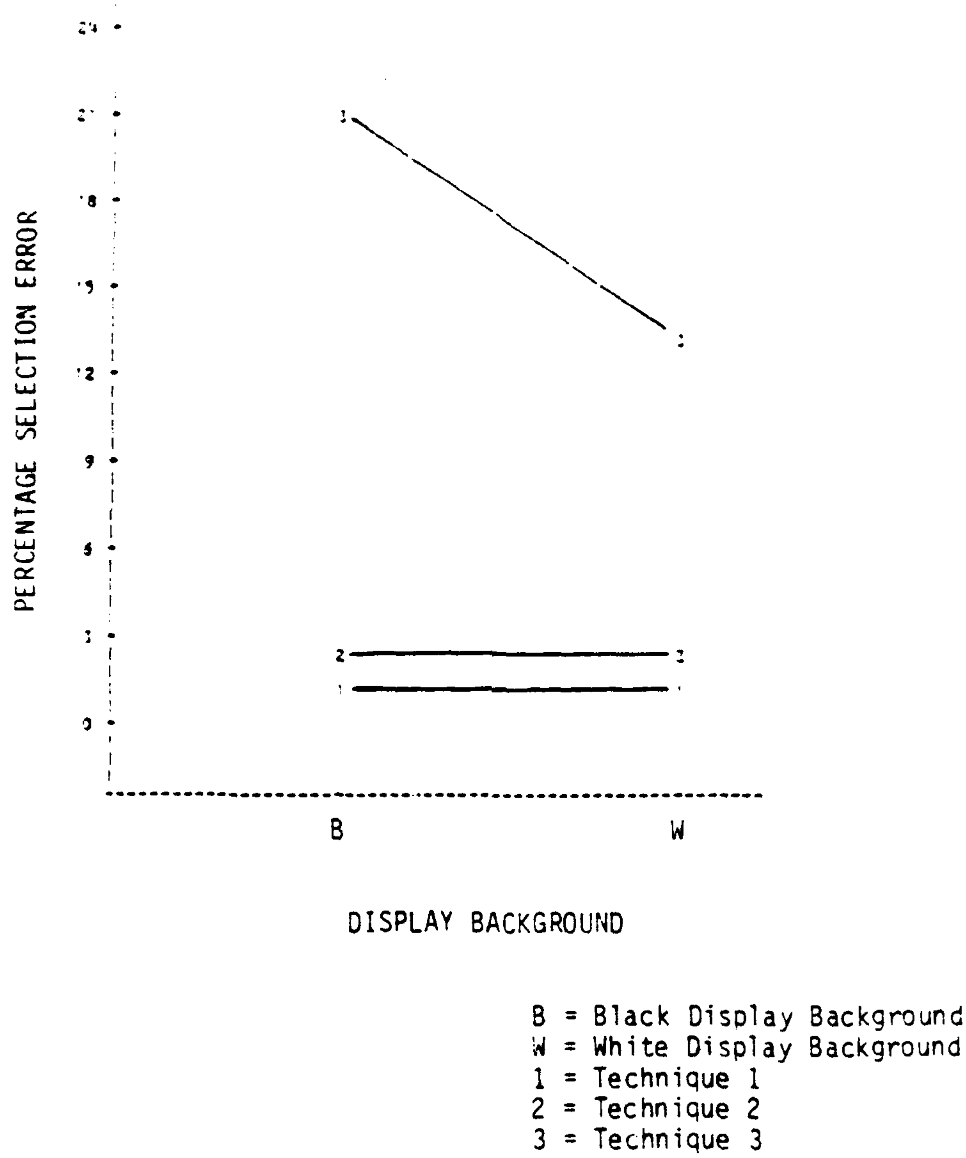


Figure 11. Plot of Coding Technique by Display Background Interaction for Percentage Selection Error.

TABLE 9. Newman-Keuls Comparisons for the Percentage Selection Error: Comparing Coding Technique by Display Background Interaction Means

Coding Technique	Display Background	Means	Comparisons	
Technique 1	White	0.25	A	
Technique 1	Black	0.27	A	
Technique 2	Black	0.47	A	
Technique 2	White	0.50	A	
Technique 3	White	2.58	A	
Technique 3	Black	4.22		B

Note: Means with the same letter are not significantly different.

TABLE 10. Newman-Keuls Comparisons for Search Time: Comparing Technique Means

Coding Technique	Means	Comparisons	
Technique 1	3.16	A	
Technique 2	3.20	A	
Technique 3	4.65		B

Note: Means with the same letter are not significantly different.

TABLE 11. Newman-Keuls Comparisons for Percentage Selection Error: Comparison of Technique Means

Coding Technique	Means	Comparisons
Technique 1	1.31	A
Technique 2	2.43	A
Technique 3	17.01	B

Note: Means with the same letter are not significantly different.

but also resulted in higher percentage selection error (8.28% error for the black background and 5.56% error for the white background display). The significant three-way CxBxT interaction depicted in Figures 8 and 9, however, indicates that these results are confounded by coding technique and foreground line thickness. The black display background achieves significantly shorter search times than the white display background when used with single pixel foreground line thickness and coding technique 3. The black display background results in significantly higher percentage selection error than the white display background when used with double pixel foreground line thickness and coding technique 3. The black display also achieved significantly shorter search times than the white display background when used with either single or double pixel foreground line thickness and coding technique 2.

The main effect of foreground line thickness was significant for search time. Double pixel line thickness resulted in shorter search times (3.51 s) than single pixel line thickness (3.83 s). The preceding analysis of the significant three-way CxBxT interaction depicted in Figure 8, however, suggests that the advantages of double pixel foreground line thickness relative to single pixel line thickness are not significant under most conditions. Double pixel line thickness appears to achieve shorter search times than single pixel line thickness when used with a white background and coding technique 1 and when used with a white background and coding technique 3.

Subjective Data

Upon completion of the study, subjects were asked to rank the twelve different coding technique/display background/ foreground line thickness combinations in order of preference (Appendix D). The results of an analysis of variance on the rankings are summarized in Table 12. The analysis shows that there was a significant difference among the 12 conditions. The results of a Newman-Keuls test are summarized in Table 13. Code sets employing coding technique 1 with any combination of display background and line thickness and the code set employing coding technique 2 with the black display background and double pixel line thickness were among the most preferred. Code sets employing coding technique 2 with either display background and single pixel line thickness and code sets employing coding technique 3 with any combination of display background and line thickness were among the least preferred.

TABLE 12. Analysis of Variance Summary Table for Subjective Data:

Source	df	SS	F	p
Between				
Subjects (S)	17	0		
Within				
Code Combinations (C)	11	1031.66	11.37	0.0001 *
C x S	187	1542.33		
Total	215	2574.00		

TABLE 13. Newman-Keuls Comparisons for Subjective Data: Comparing Code Combinations

Treatment Condition C	B	T	Means (Average Ranks)	Comparisons				
1	B	2	3.055	A				
1	W	2	3.388	A				
1	B	1	3.722	A	B			
1	W	1	5.555	A	B	C		
2	B	2	5.555	A	B	C		
2	W	2	6.166		B	C	D	
2	B	1	6.888			C	D	E
3	B	2	8.333				D	E
3	W	2	8.444				D	E
3	B	1	8.500				D	E
2	W	1	8.777				D	E
3	W	1	9.611					E

Note: Means with the same letter are not significantly different.

CHAPTER VI

DISCUSSION

Target Memorization Time

Target memorization time was greater with coding technique 3 than with the other coding techniques (Table 2). Memorization of a specific code is apparently difficult when one must distinguish one shade of gray on an absolute basis from among three possible foreground shades of gray. Memorization time was also greater with single pixel foreground line thickness than with double pixel foreground line thickness. The use of double pixel foreground line thickness resulted in a better balance of foreground area to background area in the codes. This apparently eased the task of code memorization.

Search Time and Percentage Selection Error

Subjects performed equally well using coding techniques 1 and 2. With coding technique 1 search times and percentage selection error were lower when codes were presented with double pixel foreground line thickness than when they were presented with single pixel foreground line thickness (Figures 8 and 9). Search times were lower with coding technique 2 when codes were presented on a black display background than when presented on a white display background (Figure 8). Display background had no effect on percentage selection error with coding technique 2. The fact that coding technique 2 produced results comparable to that of coding technique 1 has an important implication for the design of code sets. In situations where a designer is required to use a large number of codes to represent different areas, the use of coding technique 2 will be of particular advantage. Coding technique 2 requires half the number of textures that coding technique 1 requires to generate a given number of codes.

Performance with coding technique 3 was significantly worse than with the other two coding techniques (Figures 8 and 9). Sanders and McCormick (1987, p.52) suggest that, on the average, a person can discriminate among three to five levels of brightness. Coding technique 3 used three shades of gray to code a foreground on a background generated using a fourth shade of gray (black, dark gray, and light gray on a white background; or white, light gray, and dark gray on a black background). Discrimination among these shades of gray was apparently difficult.

Search time with coding technique 3 was longer for codes presented with single pixel foreground line thickness on a white display background than for the other three foreground line thickness/display background conditions tested (Table 7). This result may be due to a phenomenon called irradiation (Sanders and McCormick, p.86), which causes white features on a black background to appear to spread into adjacent dark areas. Black features on a white background, however, do not appear to spread. Thus, thin foreground line thicknesses that are adequate on a black background may prove to be too thin when used on a white background, where the irradiation phenomenon no longer enhances their thickness. Sanders and McCormick (1987, p.83) note that when the luminance contrast between a target and its background is low, the size of the target must be increased for it to be equally discriminable to a target with greater contrast. Because coding technique 3 employed the largest number of foreground shades of gray, some of its codes had lower contrast between target and background than any of the codes used in coding techniques 1 and 2. This suggests that it may be necessary to use thicker foreground line thicknesses with coding technique 3. Apparently the need for thicker foreground line thickness is particularly acute when dark foreground patterns are used on a white background because in this case the irradiation phenomenon does not act to enhance the apparent thickness of the foreground lines.

Pawlak (1986) cited two studies in which a light display background yielded better results than a dark display background. The effect of display background on search and selection performance in this research interacted with coding technique and foreground line thickness. Display background had no effect on performance with coding technique 1 (Tables 5 and 6). The black display background resulted in shorter search times and had no effect on selection error with coding technique 2 (Figure 8 and Table 6). The best combination of search and selection performance with coding technique 3 was achieved using codes with double pixel foreground line thickness on a white display background (Figures 8 and 9).

Subjective Data

Subjects preferred coding technique 1 with any combination of display background and foreground line thickness and coding technique 2 with the black display background and double pixel foreground line thickness. Coding technique 3 with any combination of display background and foreground line thickness and coding technique 2 with either display background and single pixel foreground line thickness were least preferred by the subjects, presumably because discrimination among codes in these code sets was difficult.

CHAPTER VI

CONCLUSION

Recommendations

An area coding system using texture and two foreground shades of gray is a practical alternative to a system using texture alone. There were no differences in memorization time, search time, or percentage selection error between two six element code sets using these two coding techniques for a memorize and search task. The results of this study suggest the following guidelines for the design of area codes:

1. If coding technique 1 is used to generate area codes, it may be employed with either a light or a dark display background. Double pixel foreground line thickness achieves better performance than single pixel foreground line thickness using this technique.

2. If coding technique 2 is used to generate area codes, it is reccommended that a dark display background be used. Performance with this coding technique is not significantly affected by the choice between single and double pixel foreground line thickness.

3. The use of code sets employing three or more foreground shades of gray is not recommended. However, when a very large number of codes is required to represent different areas, the use of this coding technique will require one-third the number of mutually discriminable textures required by coding technique 1. If coding technique 3 must be used in such situations, then it should be used with a light display background and with codes employing double pixel foreground line thickness.

Future Work

The primary hypothesis of this research was that the combination of texture and shades of gray is more effective than the use of texture alone for the coding of areas. This study used six area codes and concluded that coding techniques using texture alone and using texture and two foreground shades of gray achieved equivalent performance for memorization time, search time, and percentage selection error. A coding technique using texture and three foreground shades of gray resulted in significantly poorer performance than these two coding techniques. Thus, the primary hypothesis was not supported. There is a possibility, however, that with an increase in the number of different areas to be coded, discrimination among a large number of texture codes may be significantly more difficult than among the six textures employed in the texture only coding technique of this study. Codes employing a combination of texture and two foreground shades of gray would require half the number of textures of a coding technique employing texture alone. Thus, it is possible that as the number of different areas to be coded increases, a coding technique using a combination of texture and two foreground shades of gray will prove to be more effective than a coding technique using texture alone. An additional study could be conducted to investigate this possibility.

This study did not address the issues that arise when differently coded areas are permitted to overlap. When color is used to code areas, texture may be introduced to indicate the overlap of two differently coded areas. It is also possible to code the overlapping area using an additional color produced through some combination of the overlapping colors. Alternative approaches are necessary when texture and shades of gray are the only dimensions along which areas may be coded. The selection of textures to be used within the code set must assure that the overlap of any two textures does not produce another texture that also belongs to the code set. It would also appear to be desirable that any texture produced by the overlap of textures in the code set be readily identifiable as a combination of the underlying textures. When shades of gray are employed as a coding dimension, the overlapping of shaded areas might be indicated by an additional shade of gray produced through some combination of the overlapping shades. It is probable, however, that the number of shades of gray appearing on the display would then exceed the limited number among which a human can reliably discriminate. Additional research is needed to determine effective approaches for coding overlapping areas on monochromatic visual displays.

APPENDICES

Appendix A

Generation of Textures

The textures used in this study were generated by repetitions of the 8 x 8 pixel patterns shown in Figures 12 and 13.

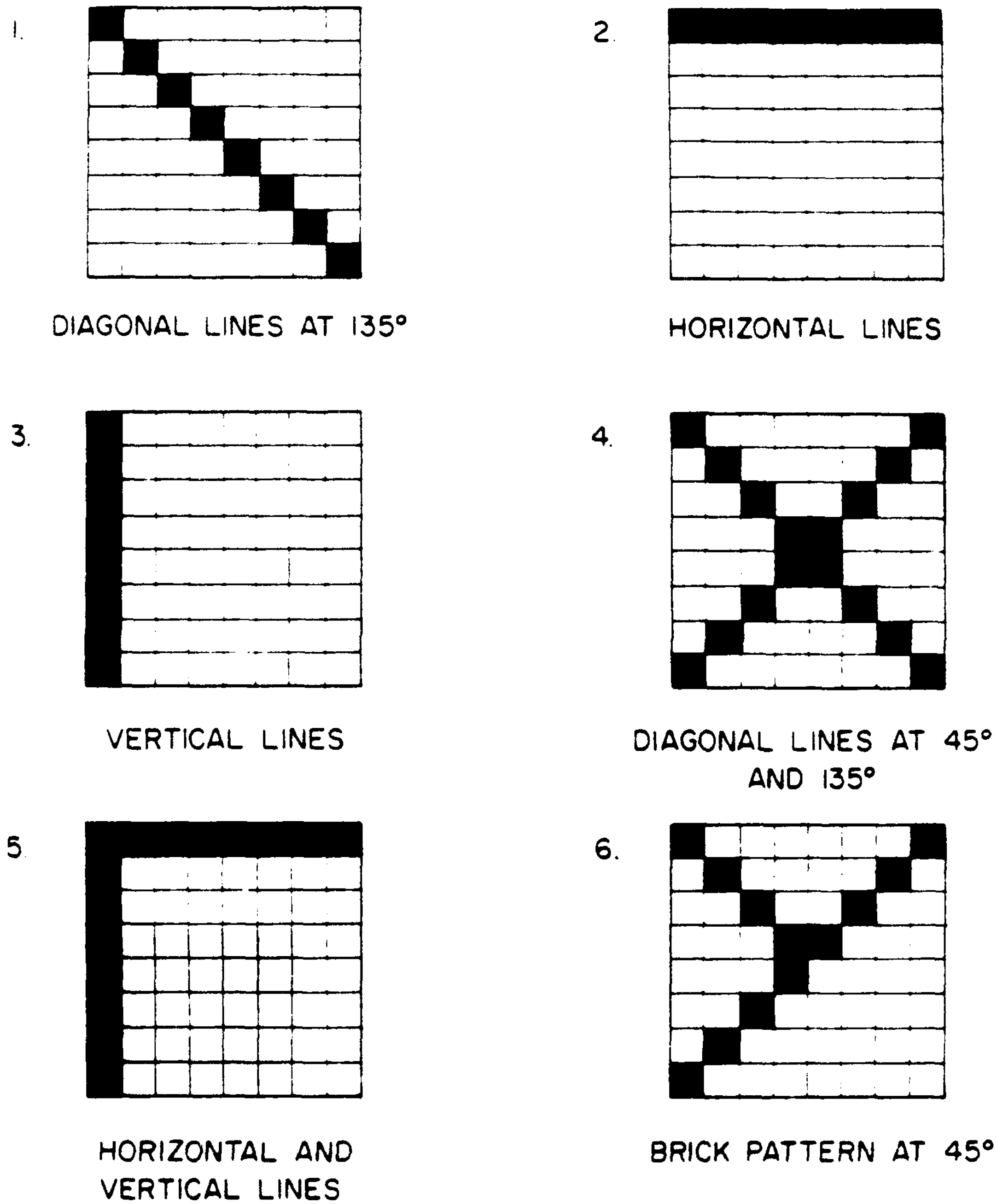


Figure 12. Single Pixel Foreground Line Thickness Patterns

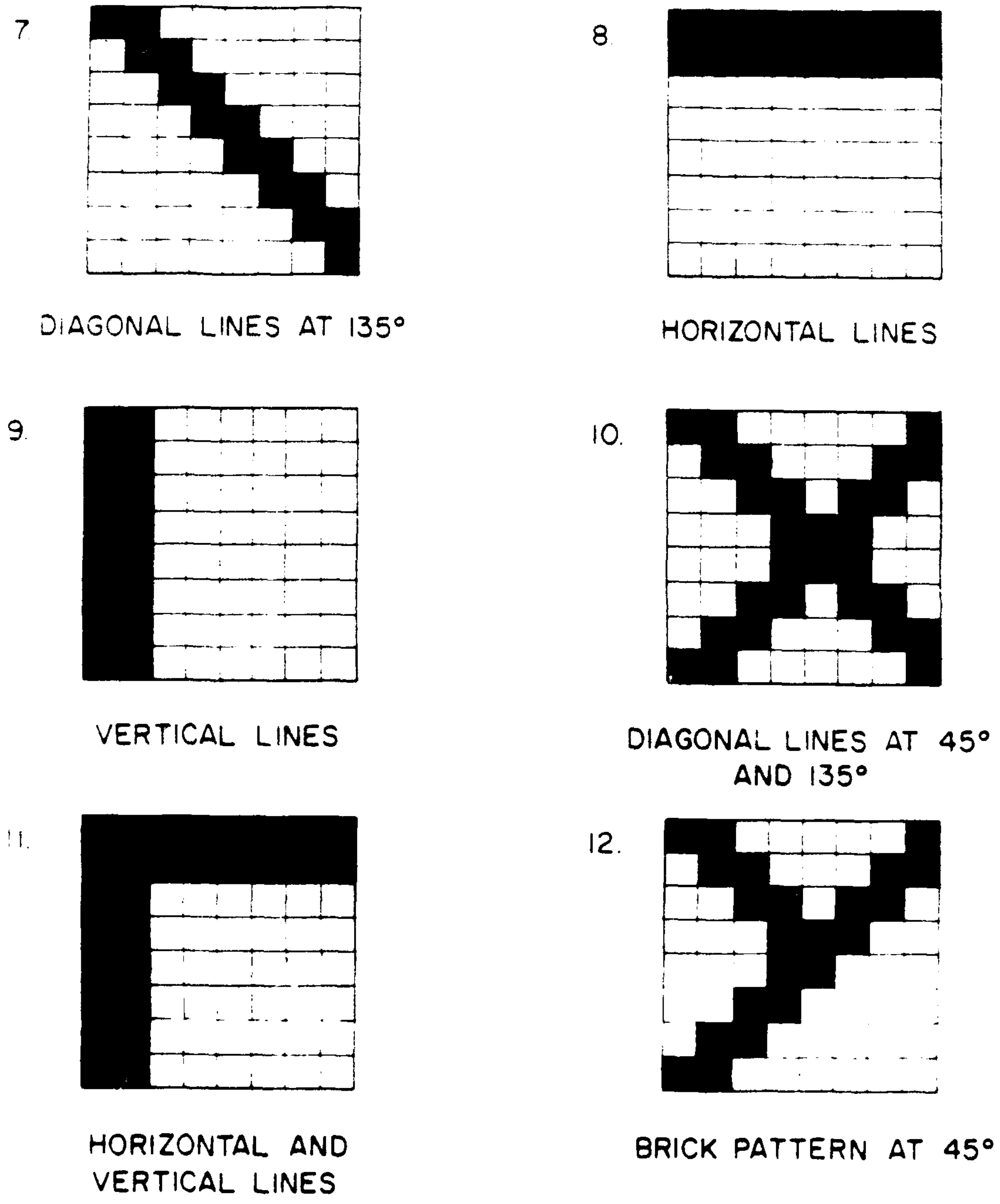


Figure 13. Double Pixel Foreground Line Thickness Patterns.

APPENDIX B

Participant's Informed Consent

The purpose of this document is to obtain your consent to participate in the experiment and to inform you of your rights as a participant.

This study investigates the use of patterns and shades of gray for coding of areas on a monochromatic visual display. Color is probably the most commonly used coding dimension for area information on maps. There are currently no specifications available to guide system designers in the use of patterns and shades of gray for coding areas. This information is needed if the different coding techniques are to be employed effectively. This research is being conducted by the Industrial Engineering Department. Dr. Joel S. Greenstein is administering this study.

Your task as a participant in this study is to look at an example code and then find two occurrences of the same code from an array of twelve coded areas. You will enter your selection using a mouse. If you choose to participate you will receive instruction in the use of the mouse and in using the system computer. The experimental session will consist of six blocks of trials with a brief rest period between blocks. The entire experiment will require about one hour and 15 minutes to complete. You will receive $5.00 for your participation in the study.

We hope that this experiment will be an interesting experience for you. It is possible that at times you may feel frustrated or stressed. Your performance on the task reflects the difficulty of the task, not your personal abilities or talents.

We may videotape your activities during the experiment. These tapes would be used to verify that the experiment is running smoothly. Please note:

1. You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the proportion of time you participated.

2. You have the right to see your data and to withdraw them from the experiment. If you decide to withdraw your data, please notify the experimenter immediately. Otherwise, identification of your parti-cular data will not be possible, because the data will be separated from your name.

3. You have the right to be informed of the overall results of the experiment. If, after participation, you wish to receive informa-tion regarding this study, please include your address (three months hence) with your signature below. If more

detailed information is desired after receiving the results summary, please contact the Department of Industrial Engineering, and a full report will be made available to you.

Your participation is greatly appreciated. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. We will answer your questions as openly as possible without biasing the experimental results. Should you have any additional questions or problems, contact Dr. J. S. Greenstein, at 656-5649.

Your signature below indicates you have read the above stated rights and you consent to participate . If you include your printed name and address below, a summary of the experimental results will be sent to you.

Signature

Printed name

Address

City, State, Zip

Appendix C

Instructions

In this experiment you will be shown a target. You are then required to select the **two occurrences** of the target that appear on a test display as quickly and as accurately as possible. You will do this by moving a display cursor with the help of a mouse. You confirm your selection by pressing the right mouse button.

You will be shown six blocks of trials. There are three code sets on which you will be tested:

A. Codes presented in black on a white background;

or

Codes presented in white on a black background;

B. Codes presented in black and dark gray on a white background;

or

Codes presented in white and light gray on a black background;

C. Codes presented in black, dark gray, and light gray on a white background;

or

Codes presented in white, light gray and dark gray on a black background;

You will view only one code set at a time. When a particular code set is being tested (A or B or C) you will be shown a block of 20 training trials with that particular code set first. On completion of the training trials, 40 test trials will be administered. You will be allowed to take a brief rest of 4 or 5 minutes after testing is complete for a particular code set (i.e., when you have finished both the training trials and the actual test trials for a code set). Do you have any questions at this time? If not, then you may read the instructions for the use of the mouse.

INSTRUCTIONS FOR THE USE OF THE MOUSE

To participate in this experiment you need to know how to use a mouse. If you have not used a mouse before, the following instructions should be sufficient to permit you to participate in this experiment.

There are two buttons on the mouse. The one on your left is called the left mouse button and the one on your right is called the right mouse button. In this experiment you need to press the **right mouse button** to confirm your choice of a target or to go to the next screen. You will never use the left mouse button and pressing it will not have any effect. You may now press the right mouse button a couple of times to gain a feel for it.

When a block of trials begins you will first be shown the set of codes that will be used in that particular block. After you have taken a good look at the codes you should press the right mouse button to view the first target. You may look at the target as long as you wish. When you think you will be able to remember it sufficiently well, you should press the right mouse button to view the test display. When the test display appears on the screen you will hear a beep and find that the cursor (in the shape of a crosshair) is placed in the lower left corner of the screen. You should move the cursor to the desired target locations and press the right mouse button to confirm each of your two choices. Each time you confirm a choice you will hear a beep. You will only have two chances and once you have made a confirmation of your selection, it cannot be changed. At this point you will be given feedback regarding the accuracy of your selections. If you then press the right mouse button, you will be shown the next target. If you have any questions at this time, you may ask the experimenter. He will attempt to answer your questions in as much detail as possible without influencing the experiment. If you do not have any questions at this time, you may ask the experimenter to begin the study. If there are any problems during the administration of the experiment you should notify the experimenter immediately.

Appendix D

Ranking Form

SUBJECT ________

During this study you actually worked with 12 different sets of codes. Each code set consisted of 6 codes. The twelve code sets are now shown on the display. Look at the display and rank the twelve code sets in order of preference, using a scale of 1 to 12, where 1 is most preterred and 12 the least preferred.

A. ____________

B. ____________

C. ____________

D. ____________

E. ____________

F. ____________

G. ____________

H. ____________

I. ____________

J. ____________

K. ____________

L. ____________

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